BILLIARDS:

Baseline Instrumented Lithology Lander, Inspector and Asteroid Redirection Demonstration System

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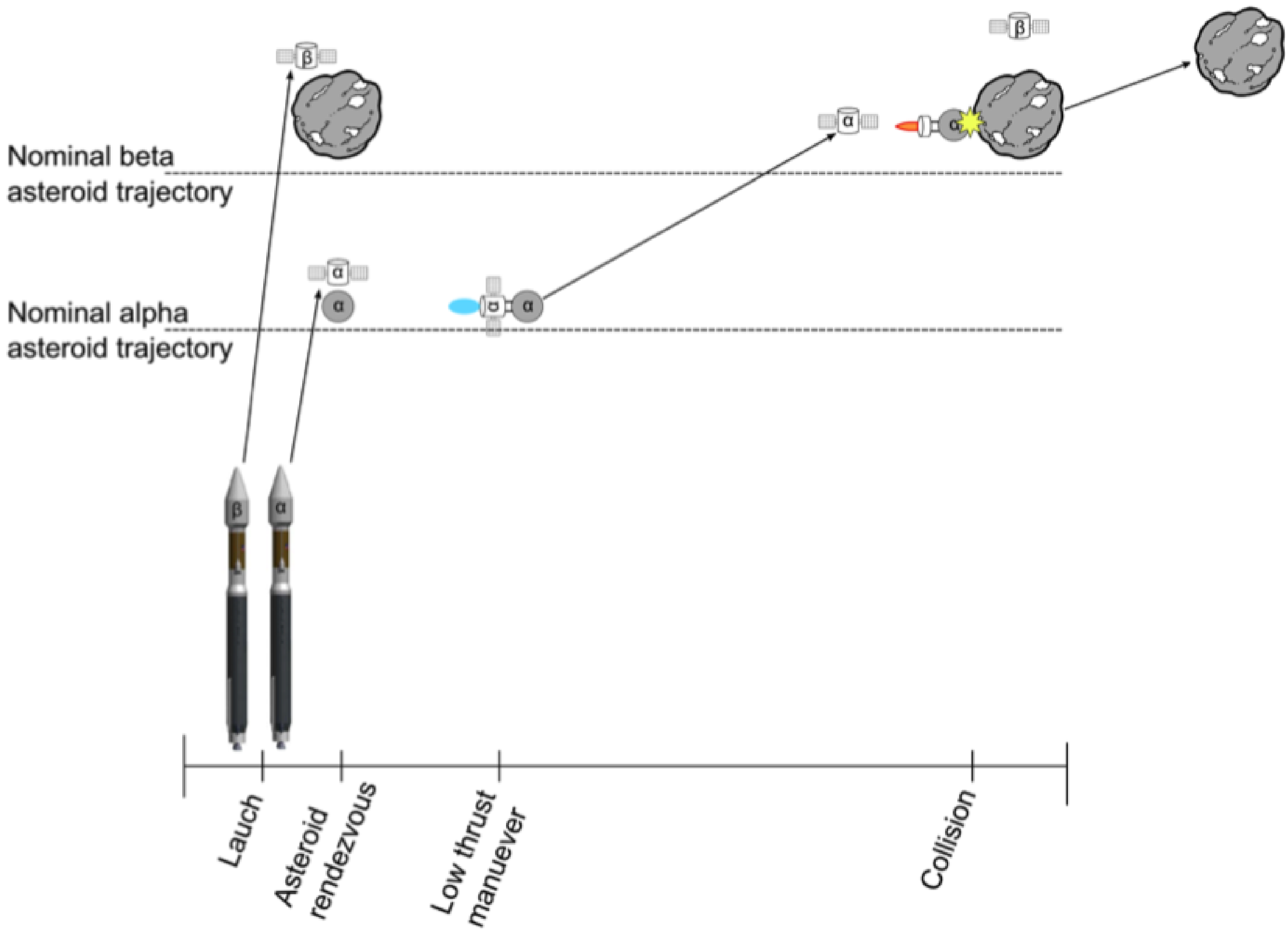
Introduction

- BILLIARDS
  - Baseline Instrumented Lithology Lander, Inspector, and Asteroid Redirection Demonstration System
  - Proposed demonstration mission for "Billiard-Ball" concept
  - Select asteroid pair with natural close approach to minimize cost and complexity
- Primary Objectives
  - Rendezvous with a small ($<$10m), near Earth (alpha) asteroid
  - Maneuver the alpha asteroid to a collision with a $\sim$100m (beta) asteroid
  - Produce a detectable deflection or disruption of the beta asteroid
- Secondary objectives
  - Contribute knowledge of asteroid composition and characteristics
  - Contribute knowledge of small-body formation
  - Opportunity for international collaboration

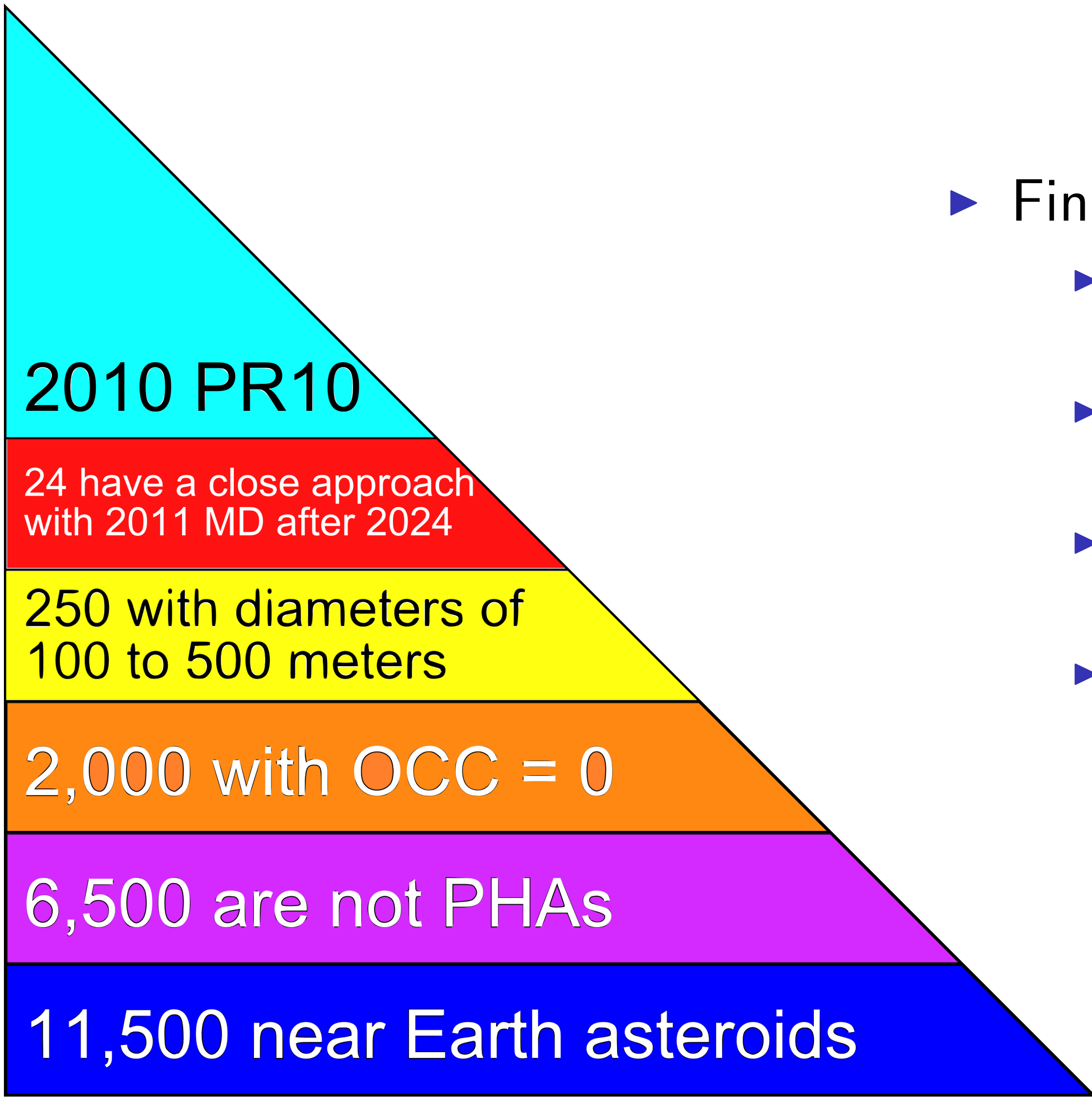
Concept of Operations



Alpha Asteroid - 2011 MD

- Physical properties
  - Absolute magnitude: 28.0
  - Diameter range: 6^{+4}_{-2} m
  - Density range: $1.1^{+0.7}_{-0.5}$ g/cm^3
- Orbital properties
  - Inclination: 2.58°
  - Semimajor Axis: 1.06 AU
  - Eccentricity: 0.0416
  - Orbit classification: Apollo

Beta Asteroid Selection

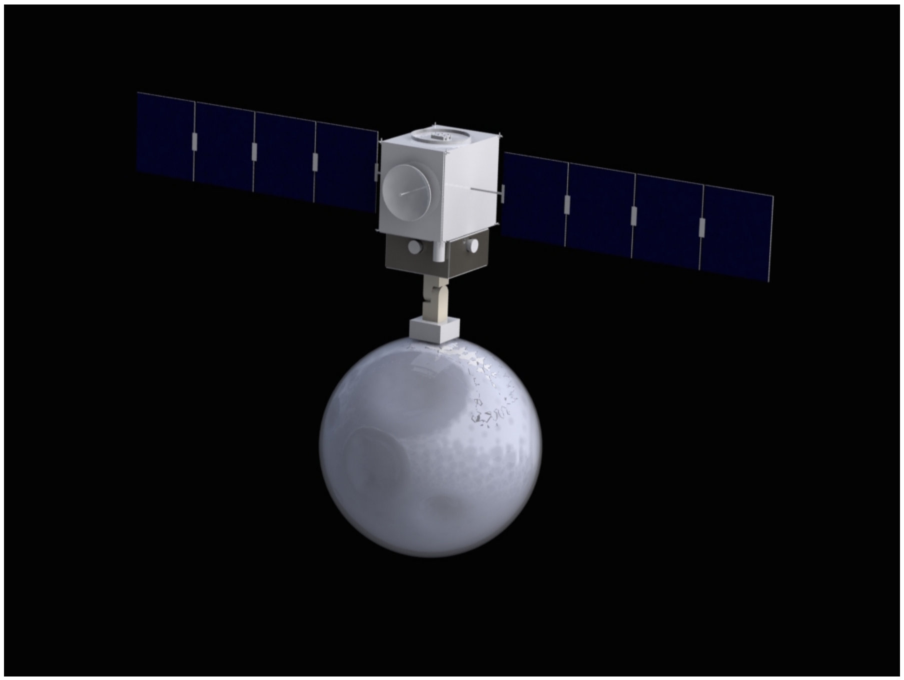


- Final Beta Asteroid Selection
  - Collision must occur with radio line of sight to Earth
  - Must be visible from space based observatories
  - Ideally visible from ground based observatories
  - Select minimum close approach distance to alpha asteroid without violating other constraints

Beta Asteroid - 2010 PR_{10}

- Physical properties
  - Absolute magnitude: 21.7
  - Diameter range: 80-356 m
  - Expected diameter: 160 m
- Orbital properties
  - Minimum natural close approach: 9.329e-3 AU
  - Inclination: 9.2°
  - Semimajor Axis: 1.2 AU
  - Eccentricity: 0.18
  - Orbit classification: Amor
- Close approach
  - Five close approaches prior to impact
  - Impact date: Jan 26, 2029
  - Impact velocity: 6.6 km/s
  - Expected Q/Q*: 9.0
    - Most likely disrupted by impact

Spacecraft Design



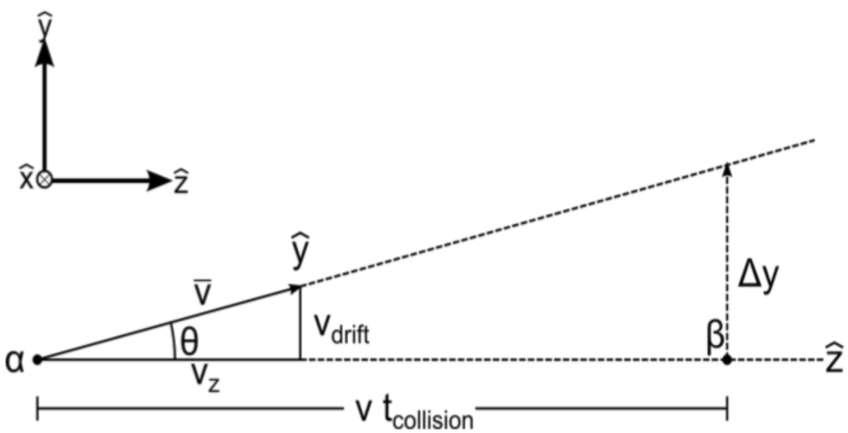
- Instrumentation Module
  - Houses most spacecraft systems
  - Provides high Isp propulsion for alpha asteroid rendezvous and redirection
  - Includes imagers for navigation and scientific data collection
- Terminal Guidance Module
  - Houses asteroid capture mechanism and internal sample instruments
  - Conducts final asteroid guidance maneuvers shortly before collision
  - High thrust propulsion for autonomous correction maneuvers

Δv Budget

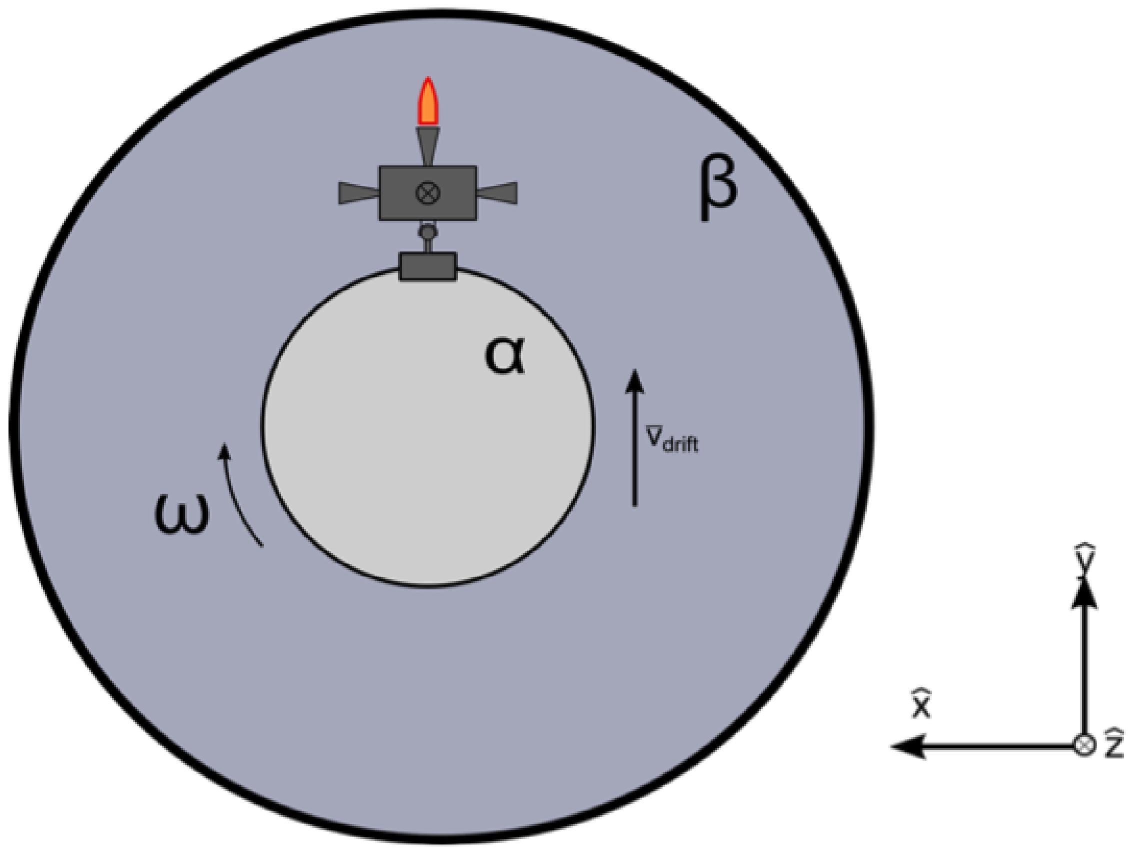
Maneuver Type	**Maneuver**	**Start Date**	Δv
<u>Launch</u> Falcon 9 v1.1 Instrumentation Module Terminal Guidance Module	Launch	July 4, 2021	$C_3 = 5.225$ km^2/s^2
<u>Low-thrust</u> Instrumentation Module Terminal Guidance Module	Alpha Rendezvous	July 11, 2021 (L+7d)	1.6 km/s
<u>Low-thrust</u> Instrumentation Module Terminal Guidance Module Alpha Asteroid	Alpha Redirect Midcourse Corrections	August 12, 2025	12 m/s 19.2 m/s
<u>High-thrust</u> Terminal Guidance Module Alpha Asteroid	Terminal Guidance Maneuvers	January 25, 2029 (I-24h)	8 m/s

Terminal Guidance - CONOPS

Alpha asteroid rotating about the position vector between the two asteroids with period T (3 min).



Note: $v_z \gg v_{drift}$



Spacecraft Mass Estimates

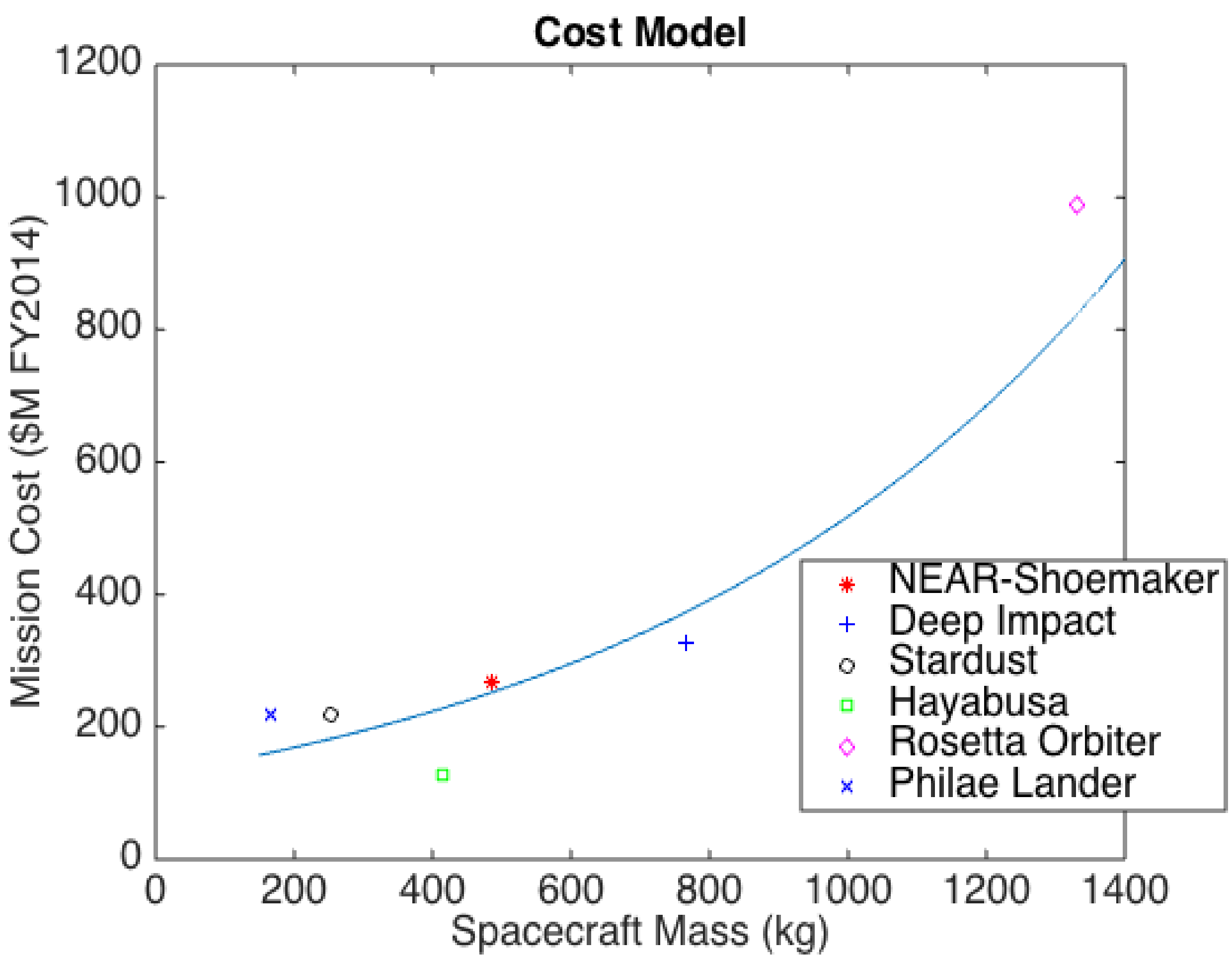
Instrumentation Module

Subsystem	Mass (kg)
Structural	240
Propulsion (dry)	120
SEP Propellant	750
RCS Propellant	50
Power System	401
Thermal	44
Data Processing	61
Attitude Control	64
Science Instrumentation	70
Total Dry	1000
Total	1800

Terminal Guidance Module

Subsystem	Mass (kg)
Structural	240
Propulsion (dry)	26
Bi-propellant	600
Power System	53
Thermal	32
Data Processing	16
Science Instrumentation	70
Capture Mechanism	310
Total Dry	687
Total	1287

FY2014 Cost Estimate



IM P&D Cost	$518M
TGM P&D Cost	$334M
Capture Mechanism Cost	$64M
Launch Vehicle Cost (Falcon 9 v1.1)	$85M
Total Mission Cost	$1001M

Conclusion

- 2011 MD (alpha asteroid)
  - Density: 1.1 g/cm^3
  - Diameter: 6 m
- 2010 PR_{10}
  - Diameter: 160 m
- Timeline
  - Earth Departure: July 4, 2021
  - Rendezvous with Alpha asteroid: July 11 2021 - December 31, 2024
  - Impact velocity: 6.6 km/s
  - Collision: January 27, 2029
- Budget
  - $1001M (FY 2014)
- Mission Objectives
  - Produce an “artificial” collision between two near-earth asteroids, testing an option for future planetary defense missions
  - Observe and confirm collision
  - Gather knowledge of asteroid physical properties
  - Gather knowledge of asteroid disruption dynamics

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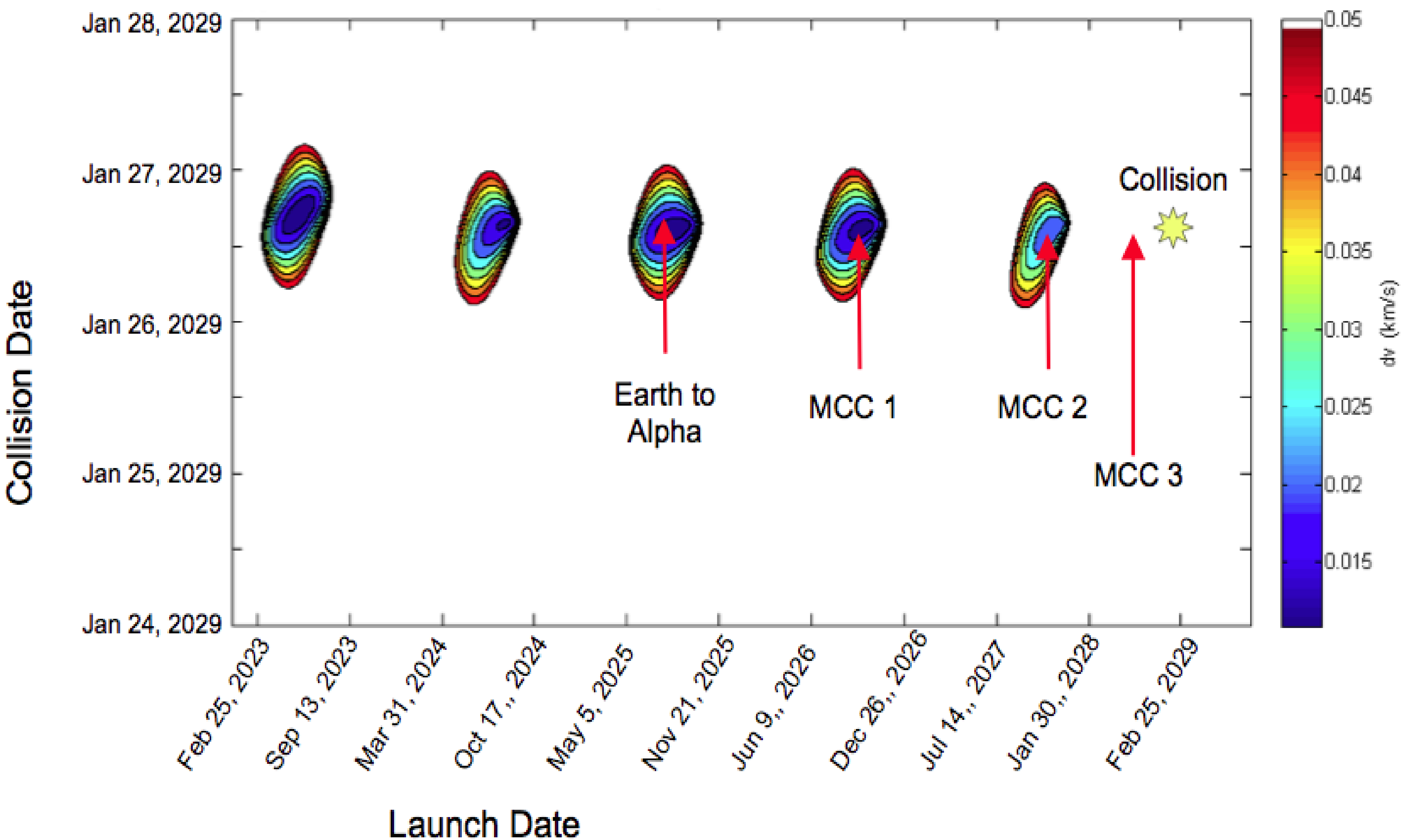
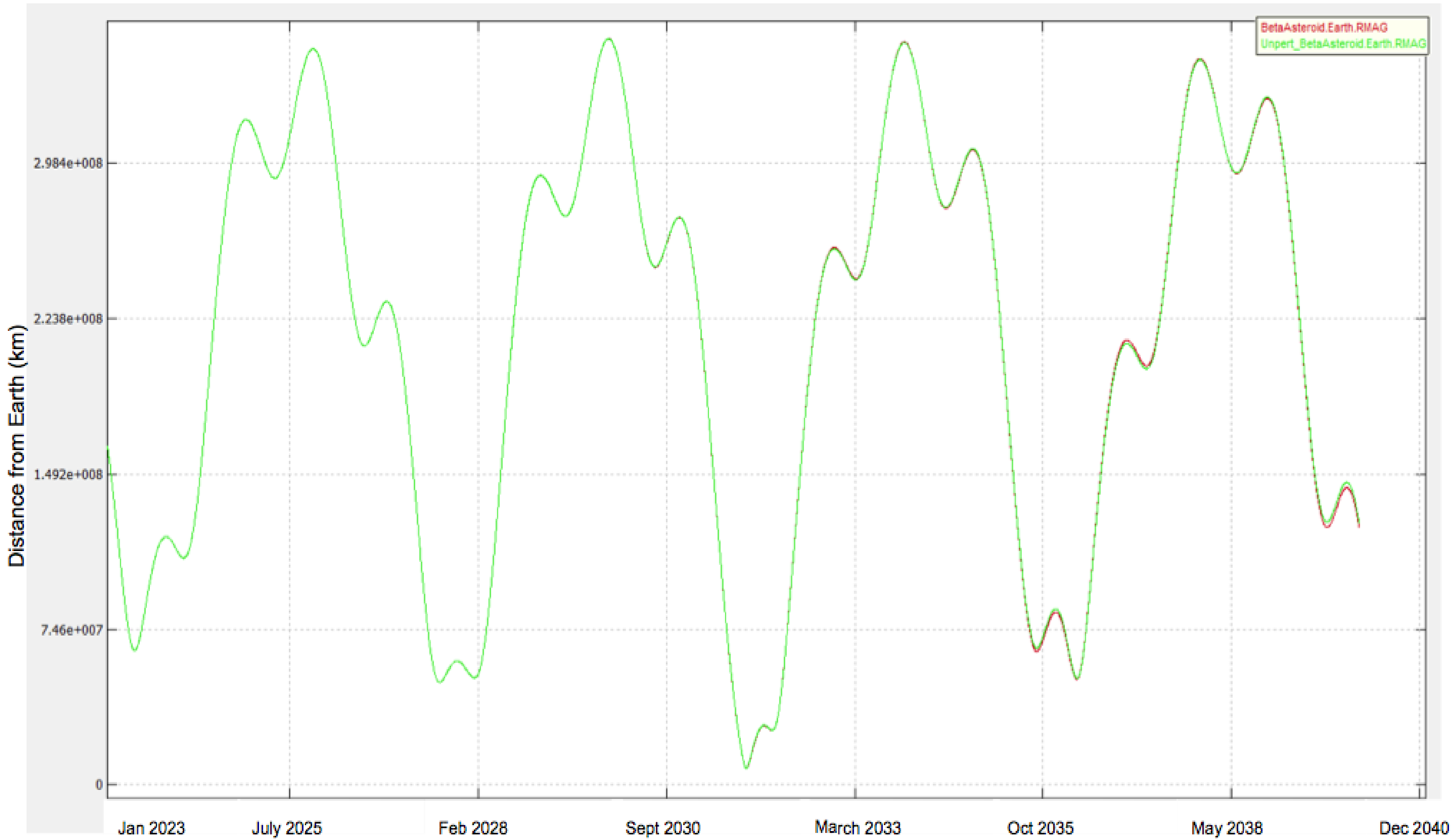
Backup Slides

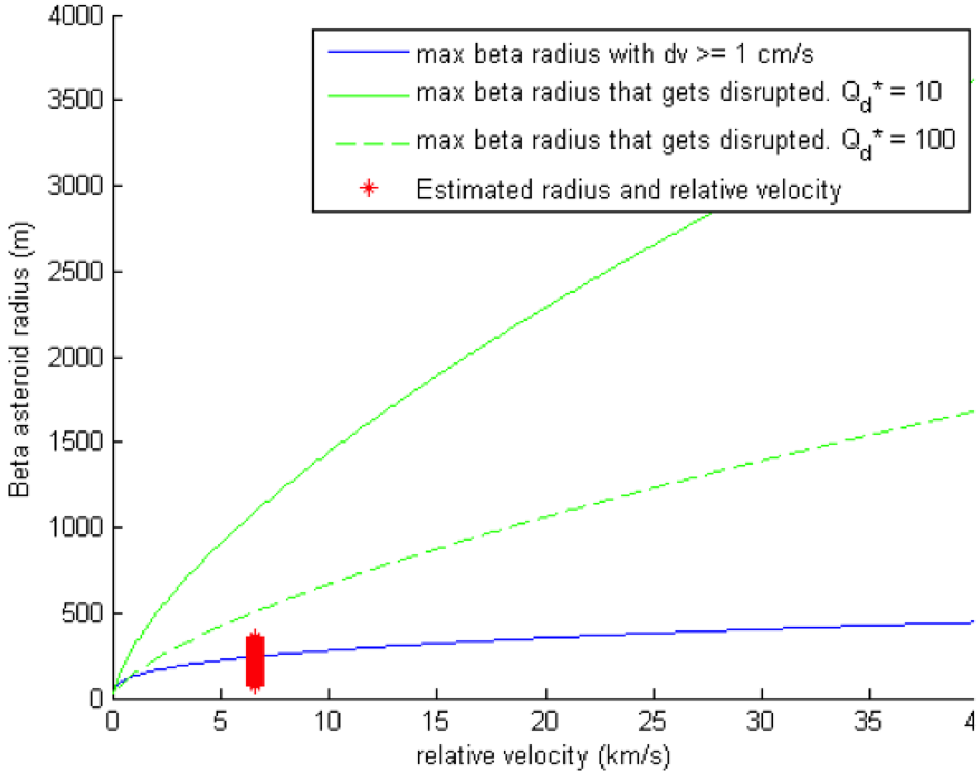
Alpha to Beta Asteroid Multi-Revolution Lambert Solver



Beta Asteroid Distance to Earth



Disruption vs. Deflection



Assumptions

Minimum detectible $\Delta v_\beta = 1\,\frac{cm}{s}$

$$m_\alpha = 130{,}000\ kg$$

$$\rho_\beta = 1400\,\frac{kg}{m^3}$$

Deflection

$$m_\alpha v_{rel} = m_\beta\, \Delta v_\beta$$

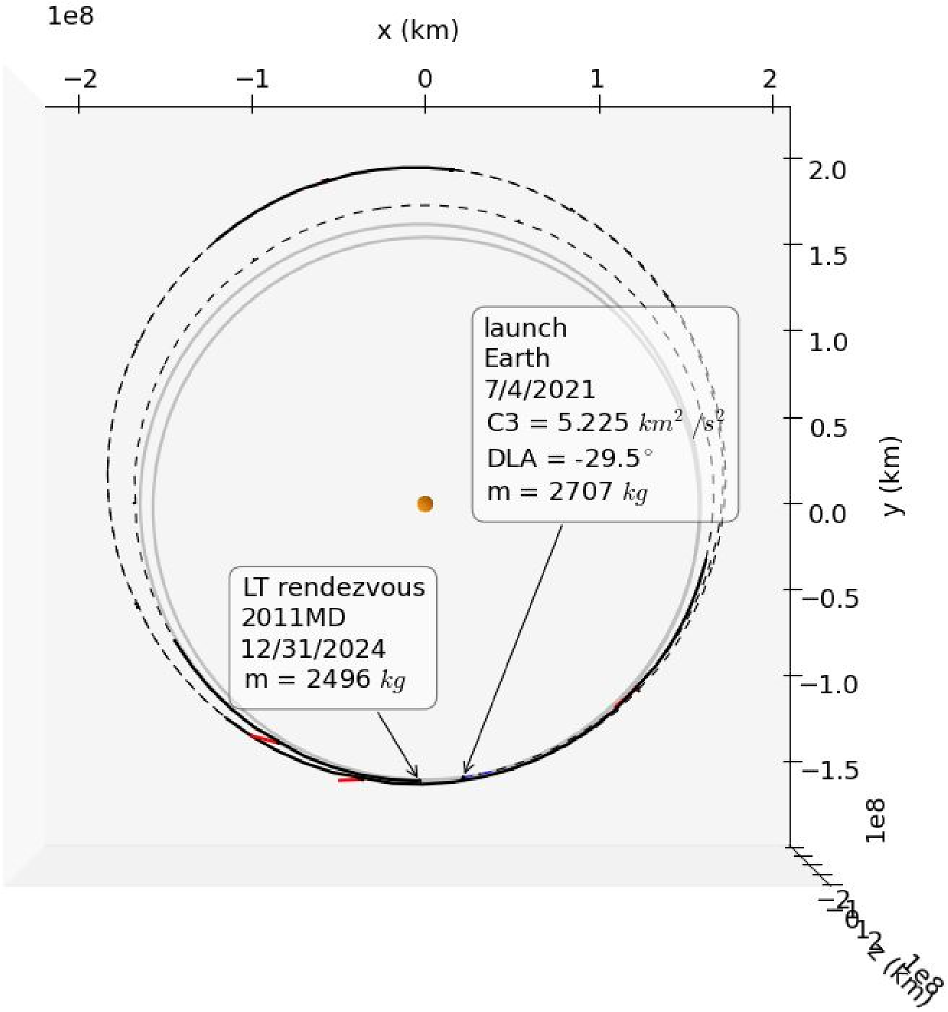
$$r_\beta = \left(\frac{m_\alpha v_{rel}}{\frac{4}{3}\pi \rho_\beta\, \Delta v_{min}}\right)^{\frac{1}{3}}$$

Disruption

$$Q = \frac{E_\alpha}{m_\beta} = Q_d^*$$

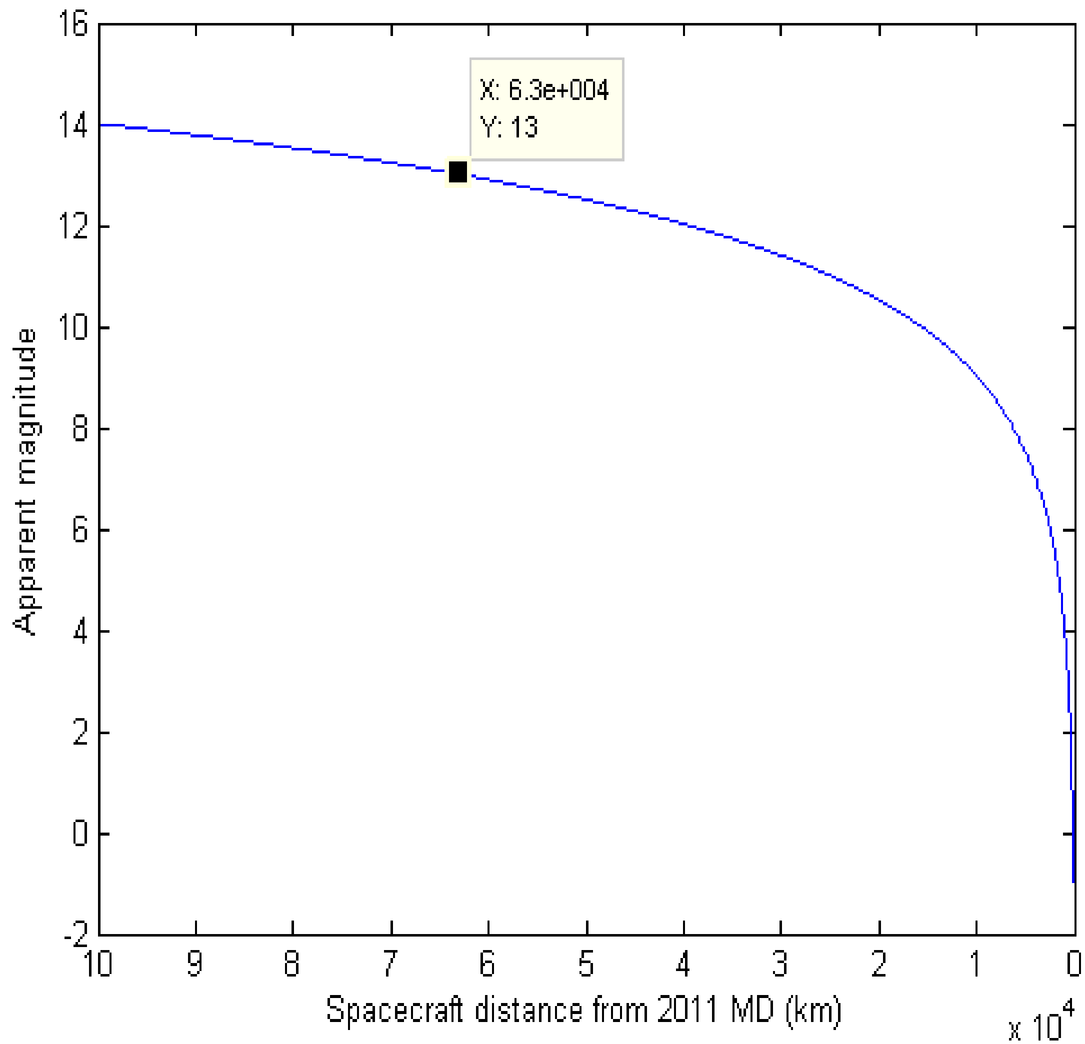
$$r_\beta = \left(\frac{\frac{1}{2} m_\alpha v_{rel}^2}{Q_d^* \frac{4}{3}\pi \rho_\beta}\right)^{\frac{1}{3}}$$

Earth to Alpha Asteroid Trajectory



Designed with EMTG.

Alpha Asteroid Apparent Magnitude



Beta Asteroid Apparent Magnitude